A Highly Tunable Sub-Wavelength Chiral Structure for Circular Polarizer

Menglin. L. N. Chen[1], Li Jun Jiang[1], Wei E. I. Sha[1] and Tatsuo Itoh[2]

[1]Dept. Of EEE,
The University Of Hong Kong

[2]EE Dept.,
University Of California, Los Angeles

Contact: menglin@connect.hku.hk

CONTENTS

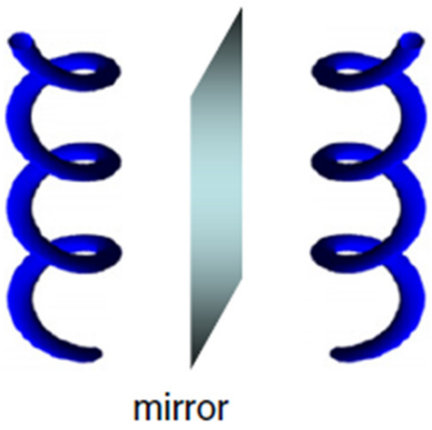
- **Introduction of chiral media**
- **Proposed chiral structure**
  - **Origin of chirality**
  - **Tunability in polarization control**
  - **Chiral circular polarizer**
- **Conclusions**

INTRODUCTION

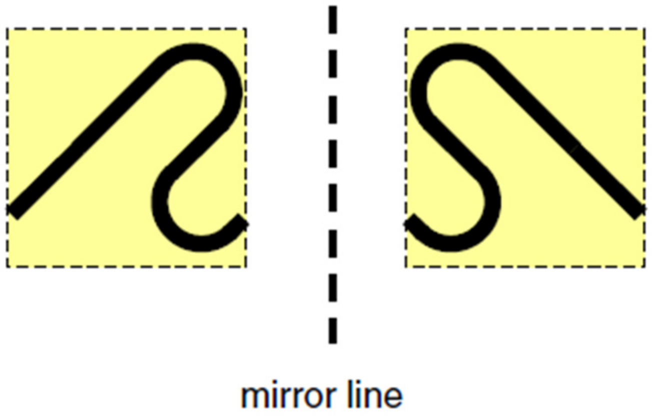
- **Chiral medium**
  - **composed of particles that cannot be superimposed on their mirror images**

- **Examples**

3D chiral structure



Planar chiral structure



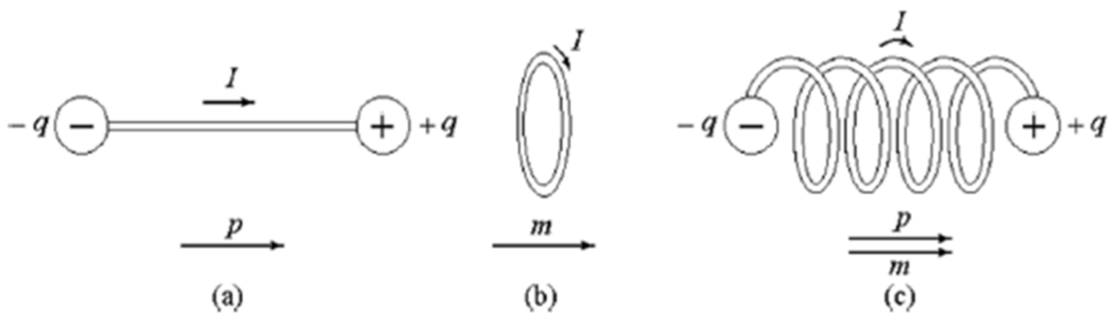
EM PROPERTY OF CHIRAL MEDIA

- BI-isotropic and BI-anisotropic media
  - Cross coupling between the electric and magnetic fields along the same direction

Constitutive relations

$$\mathcal{D} = \epsilon \cdot \mathcal{E} + \boxed{\xi \cdot \mathcal{H}}$$

$$\mathcal{B} = \boxed{\zeta \cdot \mathcal{E}} + \mu \cdot \mathcal{H}$$



- Aligned electric dipoles and magnetic dipoles appear simultaneously under the action of an electric field or a magnetic field alone.

EM WAVE SOLUTION IN CHIRAL MEDIA

- **Assume isotropic, lossless and reciprocal chiral media**

Constitutive relations

$$\begin{pmatrix} D \\ B \end{pmatrix} = \begin{pmatrix} \varepsilon_0 \varepsilon_r & -i\kappa/c \\ i\kappa/c & \mu_0 \mu_r \end{pmatrix} \begin{pmatrix} E \\ H \end{pmatrix}$$

κ, chirality that measures cross-coupling effect between electric and magnetic fields

- **Two eigenvalues**

$k_\pm = k_0(n \pm \kappa)$ $\quad n = \sqrt{\varepsilon\mu}$, refraction index of the medium without chirality

- **Two eigenvectors**

$$E_\pm = \frac{1}{2} E_0(\vec{x} \mp i\vec{y})$$

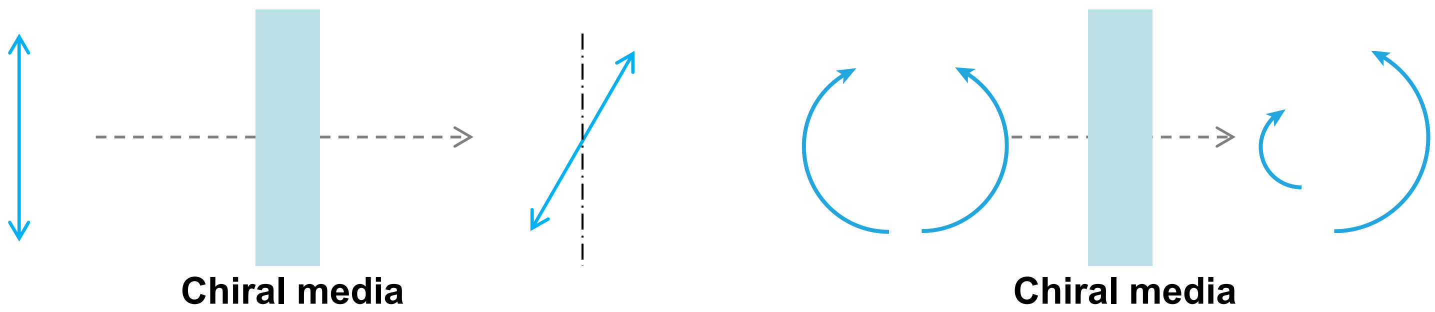
+, right circularly polarized wave; -, left circularly polarized wave

PROPERTIES OF CHIRAL MEDIA

- **Negative refraction**
  - **Negative refraction index for one circularly polarized wave when both ε and μ are positive.**

$$k_{\pm} = k_0(n \pm \kappa) \quad n = \sqrt{\varepsilon\mu}$$

- **Optical activity**
  - **Rotation of the plane of polarization of linearly polarized wave**

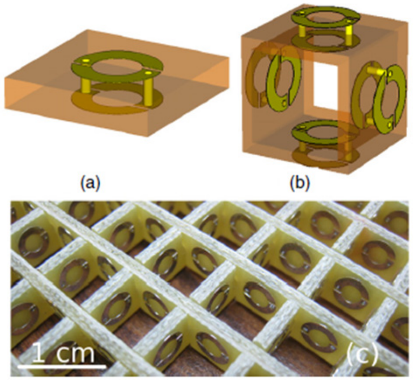


- **Circular dichroism**
  - **Different absorption of the left and right circularly polarized wave**

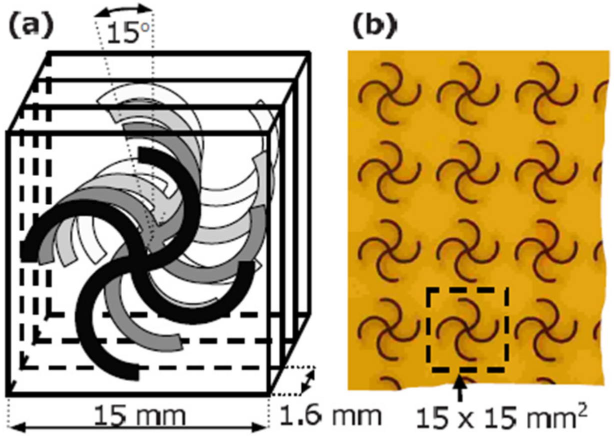
REVIEW OF CURRENT WORK

- **Existing prototypes**

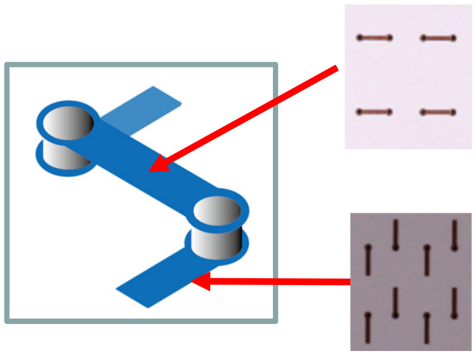
3D chiral structure[1]



Planar chiral structure[2]



- **Proposed chiral structure**
  - **Simple 3D chiral geometry**
  - **Conveniently fabricated on PCB**
  - **Great capability to manipulate the polarization state of EM waves**
  - **Large tunability**



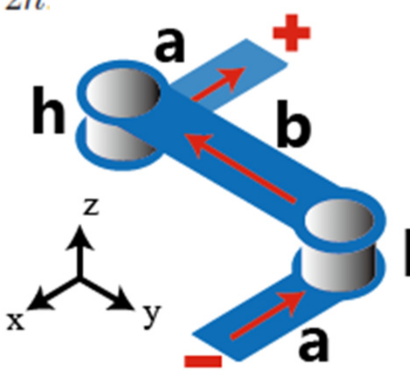
[1] B. Wang, J. Zhou, T. Koschny, and C. M. Soukoulis, "Nonplanar chiral metamaterials with negative index," *Appl. Phys. Lett.*, vol. 94, no. 15 p. 151112, Apr. 2009.
[2] E. Plum, J. Zhou, J. Dong, V. A. Fedotov, T. Koschny, C. M. Soukoulis, and N. I. Zheludev, "Metamaterial with negative index due to chirality," *Phys. Rev. B*, vol. 79, no. 3, p. 035407, Jan. 2009.

ORIGIN OF CHIRALITY

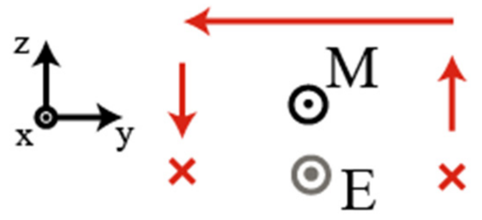
- **Fundamental mode of the proposed chiral structure**
- **Two pairs of aligned ME dipoles**

$l = 2a + b + 2h$

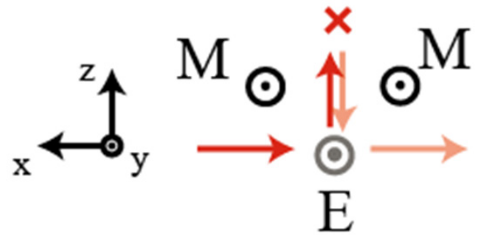
$l = \lambda_{eff}/2$



(a) 3D of the chiral particle resonating at the fundamental mode



(b) Current distribution viewed from the *x* axis and induced ME dipole pair along the *x* direction



(b) Current distribution viewed from the *y* axis and induced ME dipole pair along the *y* direction

TRANSMISSION MATRIX

- **Assume a plane wave propagates along the z direction**

$$\mathbf{E}_i(\mathbf{r},t)=\begin{pmatrix} i_x \\ i_y \end{pmatrix} e^{i(kz-\omega t)}, \quad \mathbf{E}_t(\mathbf{r},t)=\begin{pmatrix} t_x \\ t_y \end{pmatrix} e^{i(kz-\omega t)}$$

$i_{x,y}$ and $t_{x,y}$ are polarization states of incident and transmitted waves.

- **Chiral particle modelling**

Transmission matrix

$$\begin{pmatrix} t_x \\ t_y \end{pmatrix} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix} \begin{pmatrix} i_x \\ i_y \end{pmatrix} = T_{lin} \begin{pmatrix} i_x \\ i_y \end{pmatrix}$$

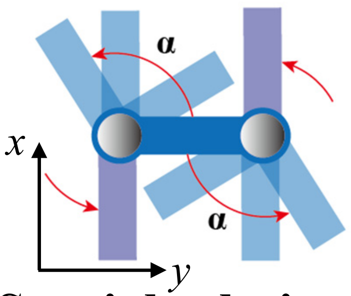
Linear basis

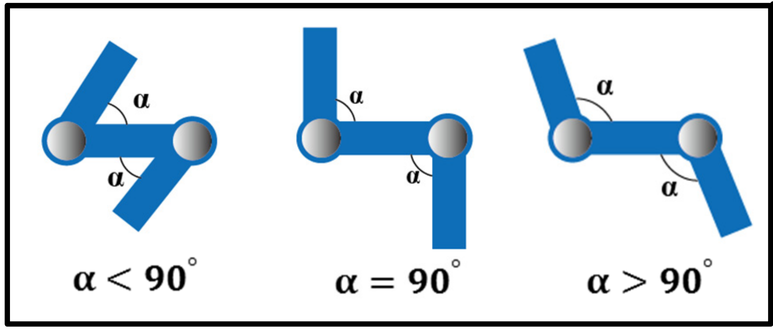
$$T_{circ} = \begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} (T_{xx}+T_{yy})+i(T_{xy}-T_{yx}) & (T_{xx}-T_{yy})-i(T_{xy}+T_{yx}) \\ (T_{xx}-T_{yy})+i(T_{xy}+T_{yx}) & (T_{xx}+T_{yy})-i(T_{xy}-T_{yx}) \end{pmatrix}$$

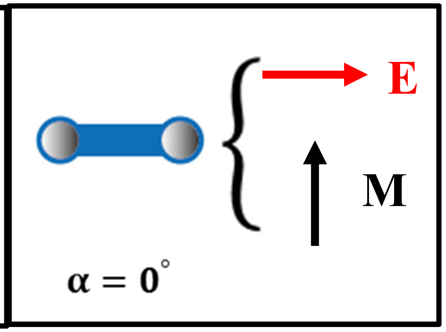
Circular basis

TUNABILITY

- **Chiral particle with different angle α**
  - **α greatly influences the direction and strength of the induced E and M dipoles, so as the chirality**

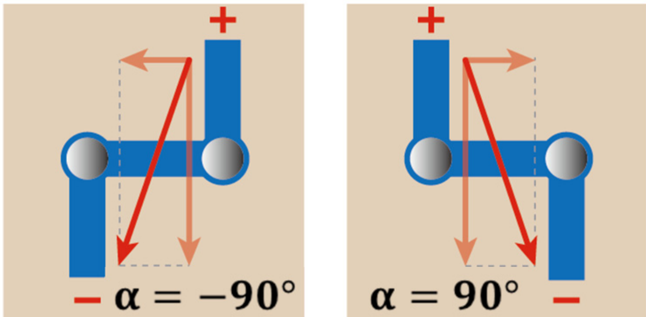






- **Special relationship for ±α**

x polarized wave



$$T_{lin}^{\alpha} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix}, T_{lin}^{-\alpha} = \begin{pmatrix} T_{xx} & -T_{xy} \\ -T_{yx} & T_{yy} \end{pmatrix}$$

$$T_{circ}^{\alpha} = \begin{pmatrix} T_{++} & T_{+-} \\ T_{-+} & T_{--} \end{pmatrix}, T_{circ}^{-\alpha} = \begin{pmatrix} T_{--} & T_{-+} \\ T_{+-} & T_{++} \end{pmatrix}$$

Optical activity: azimuthal rotation angle

$$\theta = \frac{1}{2}[\arg(T_{++}) - \arg(T_{--})]$$

Circular dichroism: ellipticity

$$\eta = \frac{1}{2}\sin^{-1}\left(\frac{|T_{++}|^2 - |T_{--}|^2}{|T_{++}|^2 + |T_{--}|^2}\right)$$

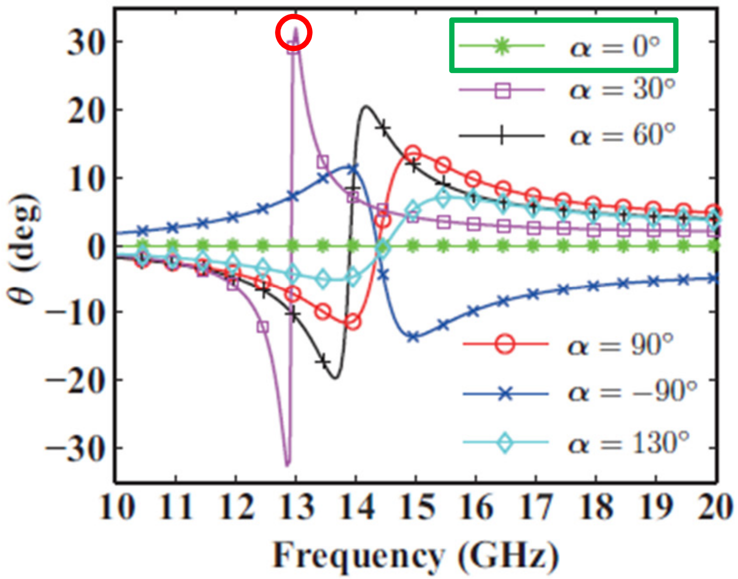
$$\theta^{\alpha} = -\theta^{-\alpha}$$

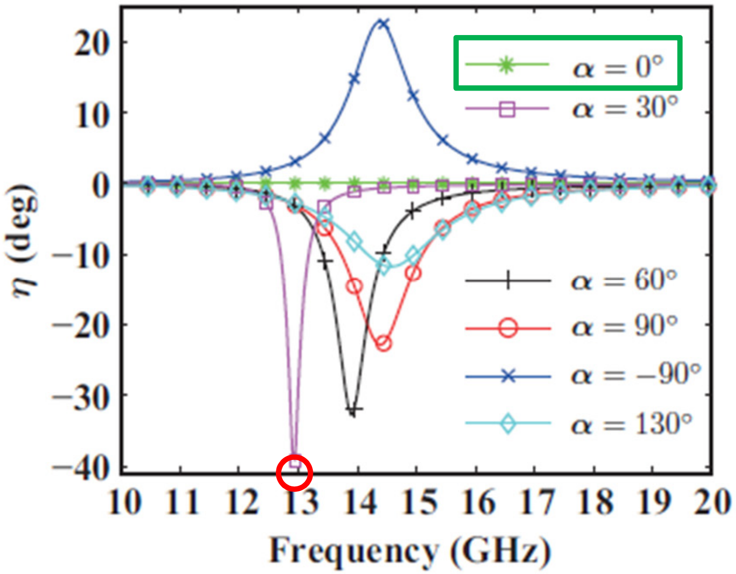
$$\eta^{\alpha} = -\eta^{-\alpha}$$

TUNABILITY (CONT.)

- **Influence of α on the polarization control of wave**
  - **Since the coupling between the ME dipoles is weaken as α increases, θ and η becomes smaller for larger α**

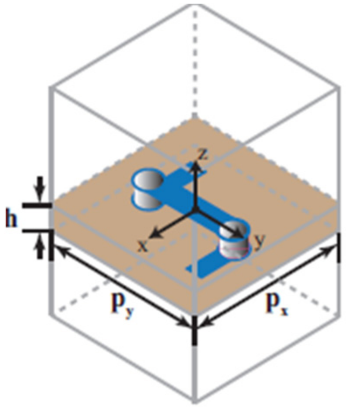
$$\theta^{\alpha} = -\theta^{-\alpha} \text{ and } \eta^{\alpha} = -\eta^{-\alpha}$$

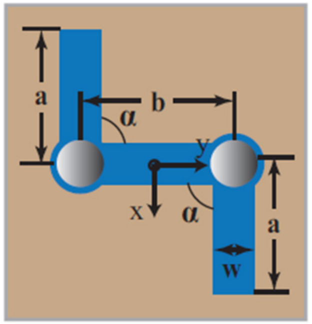




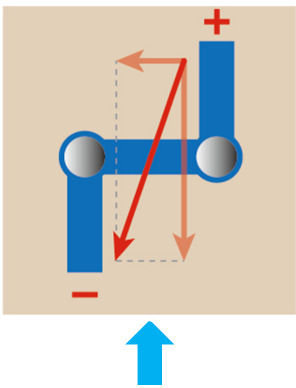
CHIRAL CIRCULAR POLARIZER

- **Convert an *x* polarized wave to a circularly polarized wave**
  - **|Txx| = |Tyx|, arg(Txx) – arg(Tyx) = ± 90°**

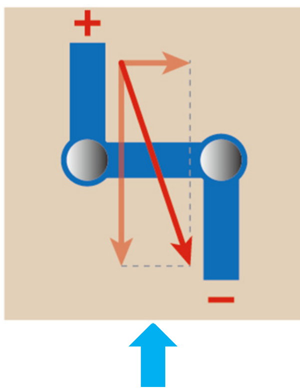




Dielectric substrate: AD600, $\varepsilon_r = 6.15$, h = 1.524 mm
Geometric parameters: a = 2.9 mm, b = 2.5 mm, w = 0.4 mm, $p_x = 7$ mm, $p_y = 6$ mm



Right-handed circular polarizer



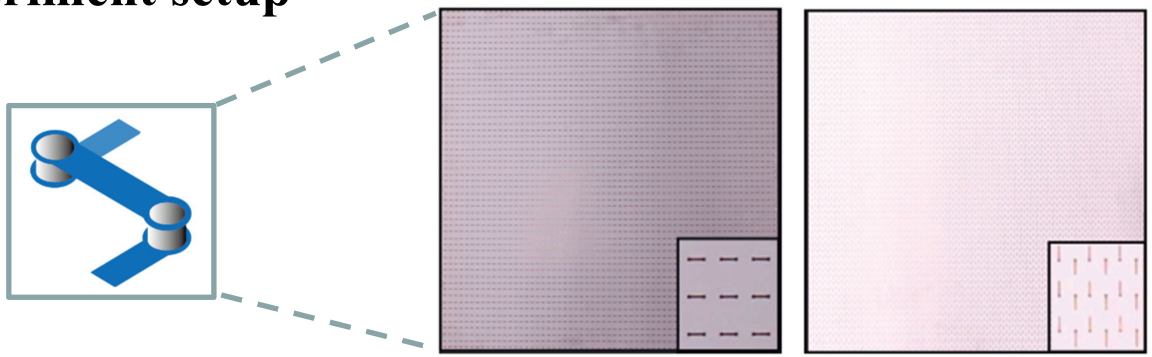
Left-handed circular polarizer

$$T_{lin}^{\alpha} = \begin{pmatrix} T_{xx} & T_{xy} \\ T_{yx} & T_{yy} \end{pmatrix}, T_{lin}^{-\alpha} = \begin{pmatrix} T_{xx} & -T_{xy} \\ -T_{yx} & T_{yy} \end{pmatrix}$$

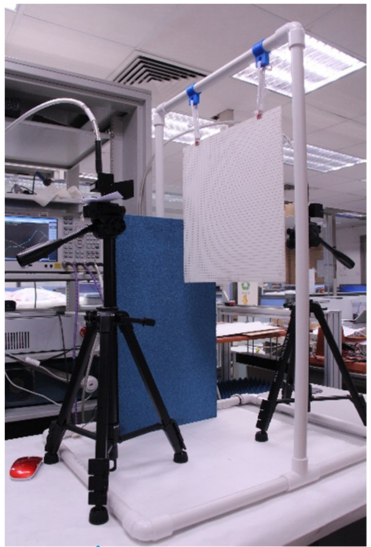
180° phase difference between the cross-polarized component by switching the orientations of the two arms

CHIRAL CIRCULAR POLARIZER (CONT.)

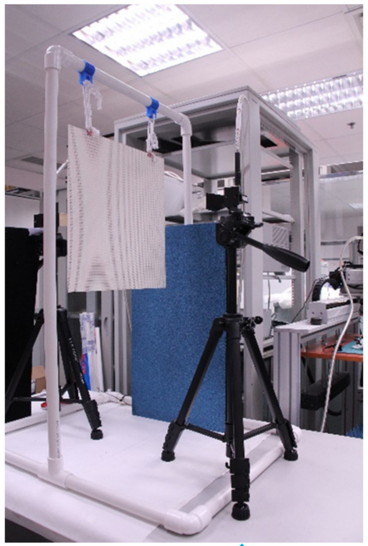
- **Experiment setup**



54 × 63 unit cells
378 × 378 mm^2



Transmitter



Receiver

Two horn antennas:
- linear polarized
- working frequency: 6.57 GHz ~ 9.99 GHz

↓ Measure

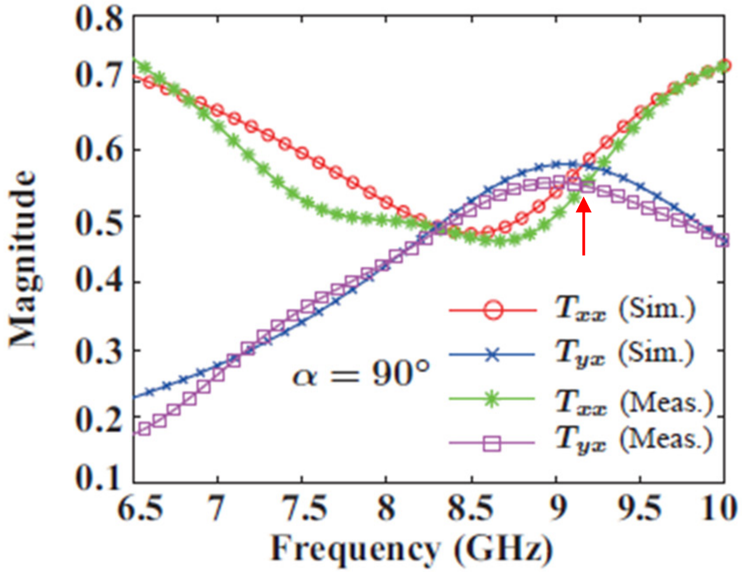
Transmission matrix in linear basis

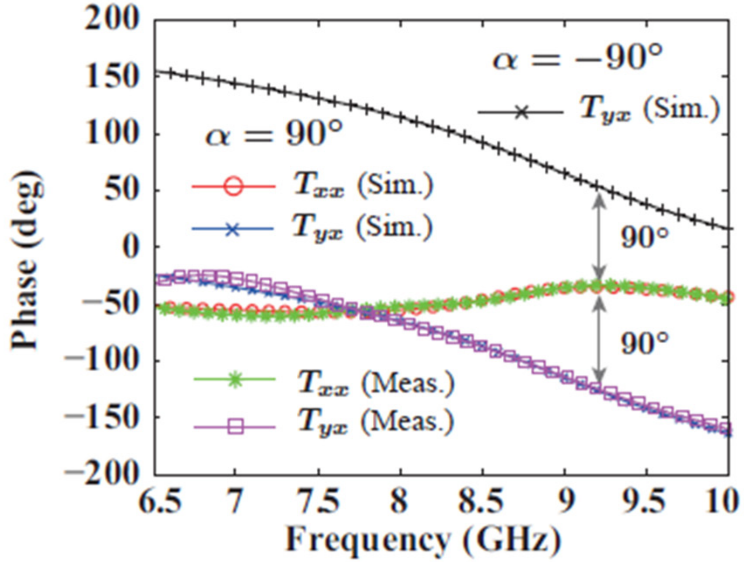
↓ Calculate

T_{circ}, θ, η

CHIRAL CIRCULAR POLARIZER (CONT.)

- Simulation and experiment results
  - Working frequency 9.2 GHz
  - Efficiency 64%
  - Compact size: unit cell size of 0.21 λ_0 × 0.18 λ_0
  - Conveniently implementation of both right- and left-handed circular polarizer





CONCLUSIONS

- **Chiral media: symmetry breaking**
- **Proposed chiral structure**
  - **No symmetry can be found along x, y and z directions, indicating a strong chirality.**
  - **There are two ME dipole, and the strengths of the E (M) dipoles can be tuned by changing the angle α. Therefore, its polarization control ability can be tuned. Simulation results of the azimuthal rotation angle and ellipticity of the structures with different αhave been shown.**
  - **Both simulated and experiment results have been shown for a right-handed circular polarizer. A left-handed circular polarizer can be easily implemented by reversing the arms.**

Reference: Menglin L. N. Chen, Li Jun Jiang, **Wei E. I. Sha**, Wallace C. H. Choy and Tatsuo Itoh, "Polarization Control by Using Anisotropic 3D Chiral Structures," IEEE Xplore, ***IEEE Transactions on Antennas and Propagation***, 2016, Accepted for Publication. http://dx.doi.org/10.1109/TAP.2016.2600758

THANK YOU

Acknowledgements:

Research Funds: the Research Grants Council of Hong Kong (GRF 716713, GRF 17207114, and GRF 17210815), NSFC 61271158, Hong Kong ITP/045/14LP, and Hong Kong UGC AoE/PC04/08.

Dr. Sha expresses his acknowledgement for the support from Prof. Wallace Choy.